Phytoplankton Productivity along CalCOFI Line 67

LT Robert W. Witzleb

22 March 2001

Naval Postgraduate School
Code 35
833 Dyer Rd. Room #304
Monterey, CA 93943-5124

rwwitzle@nps.navy.mil

Operational Oceanography
OC3570

1. Introduction

Whether or not the Earth's atmosphere is experiencing a warming climate is a subject of great debate. However, the role of green house gases and their accumulation on the global climate are becoming better understood. Many in the scientific community believe that an abundance of green house gases, primarily carbon dioxide, would serve to ultimately warm the Earth's atmosphere. Yet the concentration of carbon dioxide in the atmosphere is dynamic, being comprised of both sources and sinks. To understand the impact of mankind on the atmosphere, one must consider what natural balances exist to counter stress on this equilibrium.

Carbon ingestion within plant life is a major sink of carbon dioxide. By absorbing carbon dioxide during photosynthesis, plants are able to accumulate the carbon necessary for their structure and subsequently release oxygen. Productivity quantification of oceanic phytoplankton as well as terrestrial vegetation is important. It is speculated that the world's oceans are responsible for absorbing 18-40% of the carbon dioxide released into the atmosphere due to human activity (MacFadyen 1998). Furthermore, phytoplankton, which are microscopic, short-lived, and exist in a fluid medium, have concentrations that are highly variable in both time and space. Subsequently, efficient methods of estimating phytoplankton productivity are required. Data-sparse regions such as the world's oceans lend themselves well to remote sensing applications. However, the strengths and weaknesses of satellite-derived data must be well understood before the information they reveal may become useful.

2. Sensors

a. SeaWiFS

On August 1, 1997 NASA launched the SeaStar satellite that housed the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). SeaStar has a 705-km circular, noon, sun-synchronous orbit. The SeaWiFS instrument onboard SeaStar has an across-track scanning radiometer with eight channels operating over the 402 to 885 nm wavelength spectrum. The first six channels constitute the Photosynthetically Active Radiation (PAR) band (400-700 nm). The remaining two channels are in the Near-Infrared (NIR) spectrum (745-885 nm) (NASA 2001). Remote sensing techniques dictate that measurements of surface radiance values compensate for the atmosphere that lies between the satellite sensor and the surface being measured. By definition, the Earth's atmosphere represents one optical depth. In addition, the depth to which sunlight penetrates the oceans or the euphotic zone represents a second optical depth. Since the oceans efficiently absorb red and NIR radiation, there is nearly zero backscatter at these wavelengths. Consequently, these two wavelengths are used to quantify and remove the contribution of SeaWiFS detected radiance due to the atmosphere (Ruddick 2000). The result is remotely sensed radiance values that represent PAR scattered from the ocean's euphotic zone. Various Depth Integrated Models (DIM) exist such as the Vertically Generalized Production Model (VGPM) that are designed to transform the radiance values of the various SeaWiFS channels into a concentration of chlorophyll *a* (hereafter chlorophyll) (MacFadyen 1998). Since chlorophyll is a required ingredient for photosynthesis, it is hoped that this concentration is representative of phytoplankton productivity and thus carbon fixation. Specifically, photosynthesis is the reaction that transpires when chlorophyll is exited by exposure to PAR. The SeaWiFS instrument data provide the concentration of chlorophyll in milligrams per cubic meter (mg Chl / m^3).

b. Fluorometer

One method of obtaining *in situ* chlorophyll concentrations is by using a fluorometer. The fluorometer is an electronic device mounted on a CTD/rosette. The device contains a transmitter and a receiver arranged orthogonally. The transmitter emits blue light at 430 nm from a xenon lamp. This wavelength will excite any chlorophyll that is present. The chlorophyll subsequently emits light at the 700 nm wavelength. The fluorometer measures the amount of transmitted light at 430 nm via a reference path and compares it to the amount of received light at the 700 nm wavelength (chlorophyll fluorescence) via a signal path. It is presumed that the ratio of the reference path to the signal path is representative of the concentration of chlorophyll present. The output of the fluorometer is in volts and is directly proportional to chlorophyll concentration.

3. Additional measurement techniques

a. Direct chlorophyll

Although time and labor intensive, chlorophyll may be measured directly. By obtaining a water sample from an area and depth of interest, a known volume can be filtered to separate all the particulate matter it contains including phytoplankton. Chlorophyll pigment can then be extracted via acetone and measured to determine concentration. This is the Holm-Hansen procedure (Pennington 1999).

b. Carbon Uptake

The goal of previous sensors and measurements has been obtaining concentrations of chlorophyll within the water column. However, the objective of determining chlorophyll concentrations is to discern productivity or the rate at which plant matter accumulates carbon and thus breaks down carbon dioxide. Radioactive carbon fourteen (^{14}C) can be introduced into water samples taken throughout the water column. The samples can then be incubated in light and temperature conditions that mimic the environment from which they were obtained. After a finite incubation period, the samples can be analyzed to assay precisely the amount of ^{14}C that was assimilated (Pennington 1999). Radioactive ^{14}C is used as a label so that carbon assimilated during incubation can be easily distinguished from previously fixed carbon. This methodology yields a more precise spatial and temporal measurement of phytoplankton productivity in units of milligrams of carbon per cubic meter per day (mg C/m^3/day).

4. Data

a. In situ data

Data were obtained from two cruises conducted along California Cooperative Oceanic Fisheries Investigation (CalCOFI) line 67 upon the R/V Point Sur. The first data were collected during April 2000 and constituted an upwelling period in the Monterey Bay region. The second data were obtained during September 2000. Between the two cruises, eight stations sampled via CTD were consistent; CalCOFI line 67 stations 60 through 90 and station C1 that lies within Monterey Bay. Both data sets included, but were not limited to, chlorophyll concentration via the Holm-Hansen procedure and via a fluorometer taken at the surface and standard depths of 5, 10, 20, 30, 40, 60, 80, 100, 150, and 200 m. In addition, ^{14}C uptake was computed from the surface throughout a predetermined euphotic zone at depths corresponding to 100, 50, 30, 15, 5, 1, and 0.1% sunlight penetration. In the event that a Light Penetration Depth (LPD) did not correspond to a standard Niskin bottle depth, a sample from the nearest standard depth was used (Pennington 1999).

For this analysis, if no productivity data existed at a standard depth, the productivity value representing the depth directly above the standard depth was averaged with the value below in order to arrive at an approximation for ^{14}C uptake at that standard depth. In order to determine depth-integrated values, a sum was taken of all values between the surface and the bottom of the euphotic zone. The euphotic zone depth was determined by the shallower of the calculated depth of .1% illumination and the maximum depth at which ^{14}C uptake was observed.

b. Remote sensing data

Satellite images were obtained from the Monterey Bay Aquarium Research Institute (MBARI) Biological Ocean Group's Remote Sensing and Modeling webpage. The images are SeaWiFS chlorophyll composite images for the two months pertaining to the cruises. Composites were chosen due to the lack of availability of SeaWiFS images for the specific dates of the *in situ* data collection. The central California coast has frequent cloud cover. Consequently, coverage is available approximately one third of the year with the frequency of obtaining the entire image being on the order of 65 days (MacFadyen 1998). In each image, the pixel nearest the reported station latitude and longitude of the *in situ* data was determined and its color was interpreted against the provided scale to arrive at the concentration of chlorophyll.

5. Analysis

a. Fluorometer versus chlorophyll

Fluorometer data are in units of volts. A linear regression over all 154 data pairs of fluorometer and chlorophyll recorded during both cruises was completed. The correlation coefficient between these two data sets was .86488. In addition, the slope of the linear regression revealed that chlorophyll concentrations were on the order of twice the fluorometer voltage output. The data were analyzed collectively and then separated into their respective cruises and reanalyzed. First, all data points were analyzed. Next, all points shallower than 10 m were discarded followed by a third analysis in which only points from station C1 were discarded. The results are depicted in Table 1.

	Correlation Coefficient		Slope of the Linear Regression	
APR	All Points	**0.91874**	All Points	**0.99032**
	Below 10 m	**0.96241**	Below 10 m	**0.62141**
	Without C1	**0.93543**	Without C1	**0.63820**
SEPT	All Points	**0.93434**	All Points	**2.64361**
	Below 10 m	**0.81766**	Below 10 m	**1.15954**
	Without C1	**0.89953**	Without C1	**0.63305**
ALL	All Points	**0.86488**	All Points	**2.01509**
	Below 10 m	**0.81077**	Below 10 m	**0.85798**
	Without C1	**0.91882**	Without C1	**0.59420**

TABLE 1. Statistical analysis of *in situ* collected chlorophyll *a* (mg/m^3) as the dependent variable and CTD/rosette mounted fluorometer output (volts) as the independent variable for two cruises conducted along CalCOFI line 67 during 2000.

Interestingly, the discarding of shallow data and station C1 data for the April cruise served to improve the correlation in both cases where the correlation for September cruise data was degraded. Overall, failure to consider station C1's data substantially improved the data correlation. The strongest correlation was in April for depths greater than 10m (Fig. 1). This is consistent with the convention that chlorophyll receiving solar illumination is less likely to fluoresce when being radiated by the fluorometer's xenon bulb. Noteworthy is the comparatively large slope of the linear regression for September only data. During this period, unusually high concentrations of chlorophyll were recorded for the shallower depths of station C1 with accompanying high fluorometer voltage outputs.

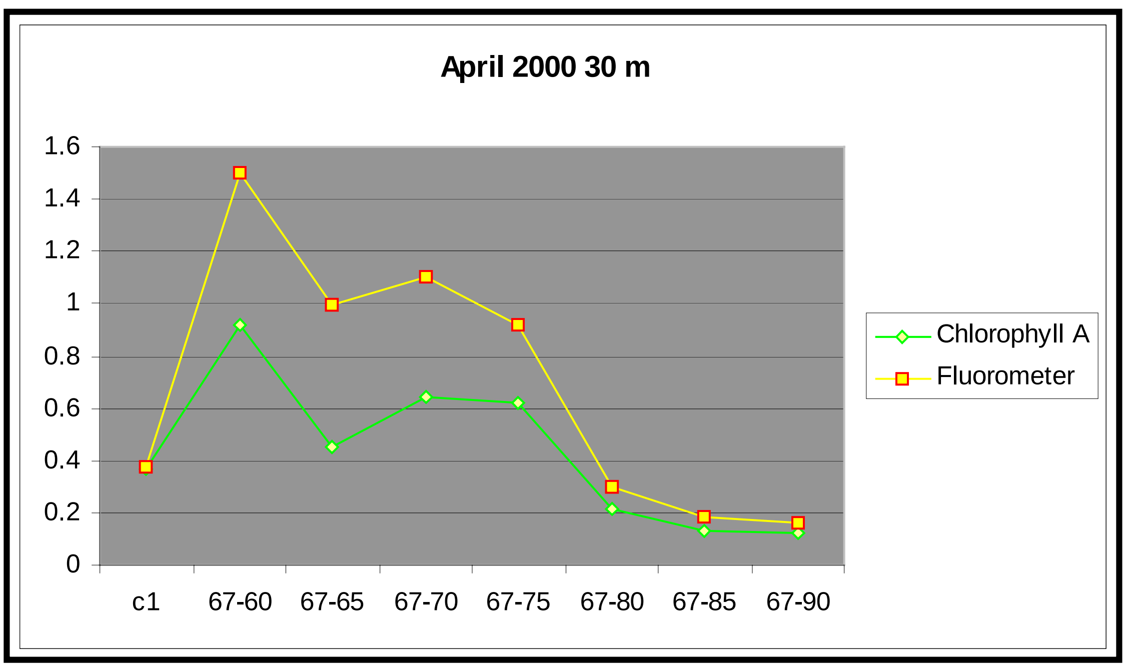

FIG. 1. A representative plot of sampled chlorophyll *a* (mg/m^3) and fluorometer output (volts) for 30 m depth along CalCOFI line 67.

When all data points where recorded chlorophyll concentrations in excess of 2 milligrams per cubic meter were discarded, the resulting correlation coefficient was .88439 and the slope of the linear regression was .59662 (Fig. 2).

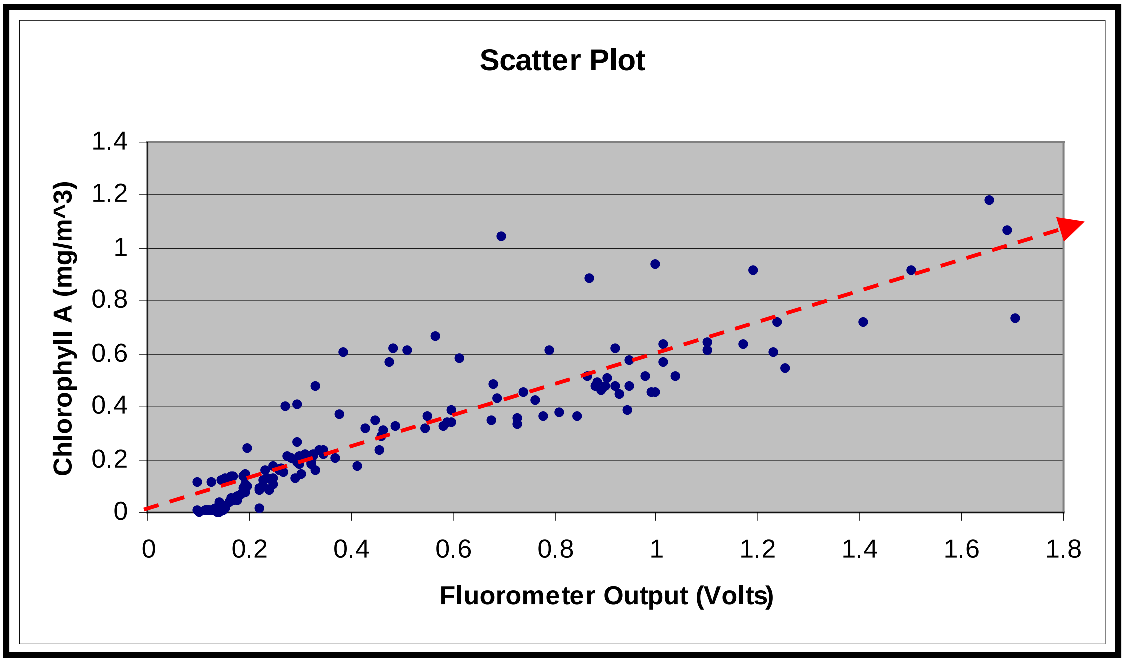

FIG. 2. Scatterplot of CalCOFI line 67 chlorophyll *a* concentration (mg/m^3) as a function of fluorometer output (volts). All data where chlorophyll concentration was less than 2 mg/m^3 are plotted. Note the linear regression slope equal to .59662.

The analysis revealed that the slope of the linear regression increased markedly as the concentration of chlorophyll and accompanying fluorometer voltage increased. Thus, if one is seeking an approximation for chlorophyll concentration based on a fluorometer voltage, it is advisable to note the range of fluorometer voltage readings. In some instances, the magnitude of chlorophyll concentration exceeded fluorometer voltage output. For the vast majority of this data, fluorometer output was confined to less than four volts. In such cases, a chlorophyll concentration equal to .6 times that of fluorometer voltage was an accurate approximation.

b. SeaWiFS

Data from SeaWiFS and direct chlorophyll measurement are both in units of milligrams of chlorophyll per cubic meter (mg chlorophyll/m^3). Productivity data are measured in milligrams of carbon per cubic meter per day (mg C/m^3/day) and are typically two orders of magnitude greater than that of the aforementioned data. Where a graphical comparison of these data was undertaken, units of decigrams of carbon per cubic meter per day were used for productivity (dg C/m^3/day).

SeaWiFS data have known difficulty in coastal regions owing to the fact that the sensor is calibrated using a marine optical buoy located off of Hawaii. These waters are not representative of most coastal waters. Thus, SeaWiFS typically overestimates chlorophyll concentrations. This error is most pronounced within 100 km of the coastline (MacFadyen 1998). In addition, because SeaWiFS overestimates the radiance contribution due to aerosol and molecular (Rayleigh) scattering of the atmosphere, frequently negative chlorophyll concentrations are reported. These impossible values are simply represented as zeros. However, the validity of data directly surrounding these regions is also suspect (MacFadyen 1998). Comparison of SeaWiFS with other data yielded the results displayed in Table 2.

CORRELATION COEFFICIENT BETWEEN:	SeaWiFS and CHLOROPHYLL	SeaWiFS and FLUOROMETER OUTPUT	SeaWiFS and CARBON UPTAKE
APRIL	**0.87647**	**0.60769**	**0.95008**
SEPTEMBER	**0.99511**	**0.94317**	**0.97214**
ALL	**0.57270**	**0.61575**	**0.89760**

TABLE 2. Correlation between the various *in situ* data and SeaWiFS derived chlorophyll *a* concentrations.

Considering that the goal of satellite-derived chlorophyll concentrations is to estimate productivity, SeaWiFS data appear to correlate well with actual measured productivity during both cruises. This is clearly true in September where SeaWiFS data fared well with all three data sets (Fig. 3).

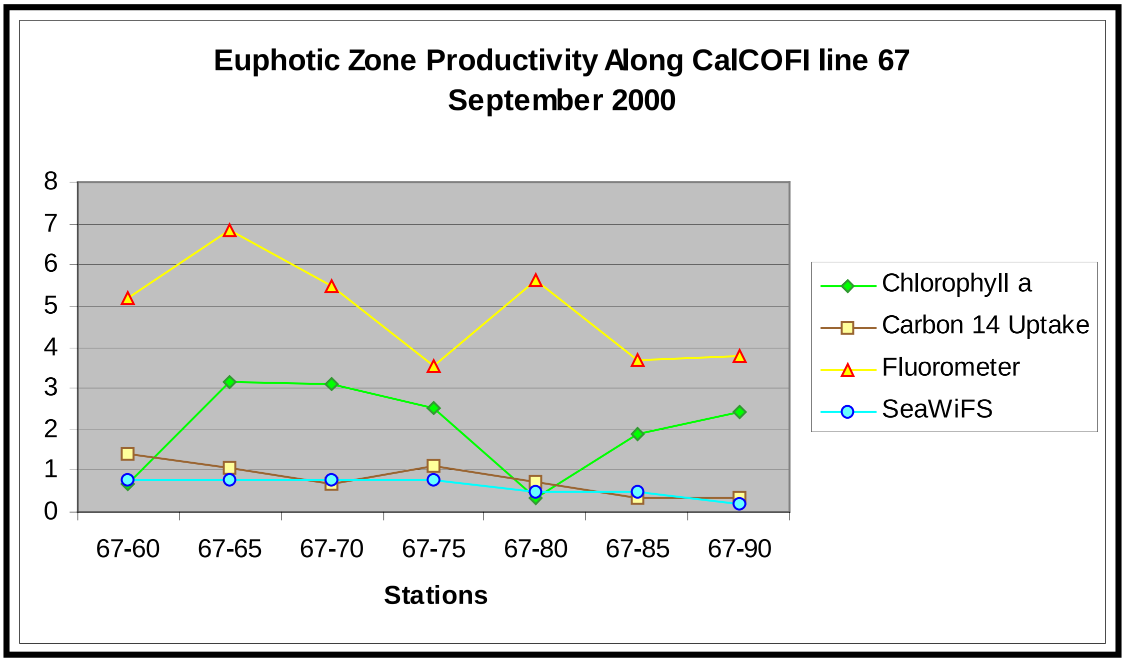

FIG. 3. Data for all stations except C1 are displayed. Although correlation was high throughout the data, the anomalously high C1 data were not plotted so that the remaining data points could be better viewed. Note the close agreement between SeaWiFS derived chlorophyll *a* concentrations (mg/m^3) and measured productivity via ^{14}C uptake (decigrams C/m^3/day). Chlorophyll *a* (mg/m^3). Fluorometer (Volts).

c. Carbon 14 uptake

The most precise measure of phytoplankton productivity is clearly ^{14}C uptake. Considering that a target water sample can be analyzed to determine the exact quantity of ^{14}C assayed during a finite time within conditions that duplicate the environment, this method provides data unmatched in spatial and temporal resolution. However, on a global scale, it is impractical. One would hope that a determination of more easily sampled quantities would yield acceptable approximations. Table 3 shows the correlation of *in situ* chlorophyll and fluorometer output with ^{14}C assimilation.

CORRELATION COEFFICIENT BETWEEN:	CARBON UPTAKE and CHLOROPHYLL	CARBON UPTAKE and FLUOROMETER OUTPUT
APRIL	**0.95961**	**0.64701**
SEPTEMBER	**0.95192**	**0.93956**
ALL	**0.76558**	**0.77837**

Table 3. Correlation of ^{14}C uptake (mg/m^3/day) to *in situ* chlorophyll *a* (mg/m^3) and fluorometer output (volts).

Individually, both April and September data agree well with productivity measurements. However, over all data points the correlation drops markedly. The fluorometer measures chlorophyll by fluorescence. The exchange of electrons via this mechanism differs from that of photosynthesis. Since productivity is associated with photosynthesis, weak correlation between carbon uptake and fluorometer output is not surprising (Cotton 1998). The strong agreement in data during April 2000 is apparent in Fig. 4. The correlation was also high in September. An examination of Fig. 5 shows the extremely high concentration of chlorophyll at station C1 and the associated increase in productivity.

Productivity levels throughout the euphotic zone were comparable for April and September at station C1. However, September chlorophyll concentrations were measured at over three times that of April. Despite the fact that SeaWiFS is known for overestimating coastal chlorophyll concentrations, satellite-derived data for September reflected levels commensurate with sampled chlorophyll concentrations at C1.

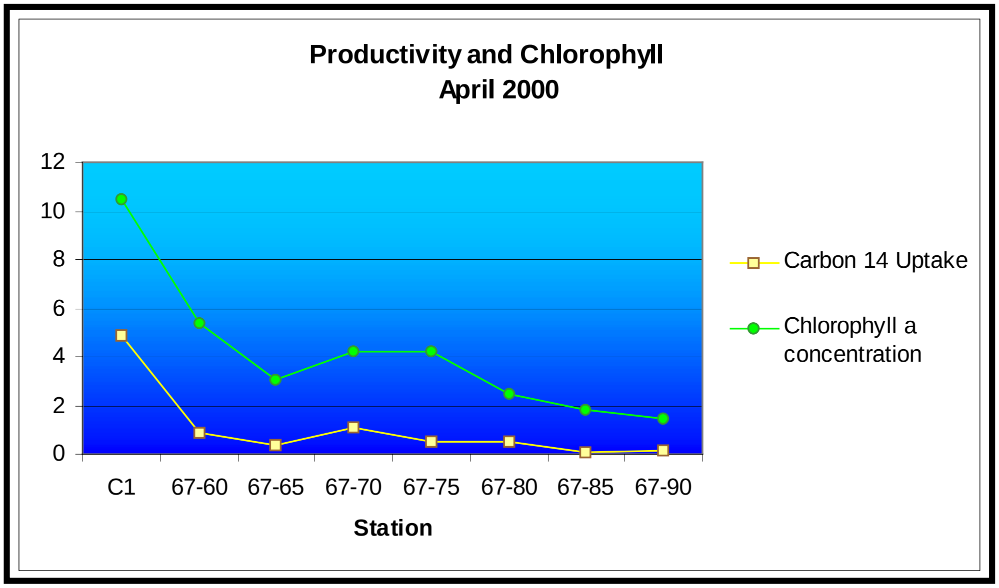

FIG. 4. Comparison between *in situ* chlorophyll *a* concentration (mg/m^3) and productivity (dg C/m^3/day) for CalCOFI line 67during April 2000.

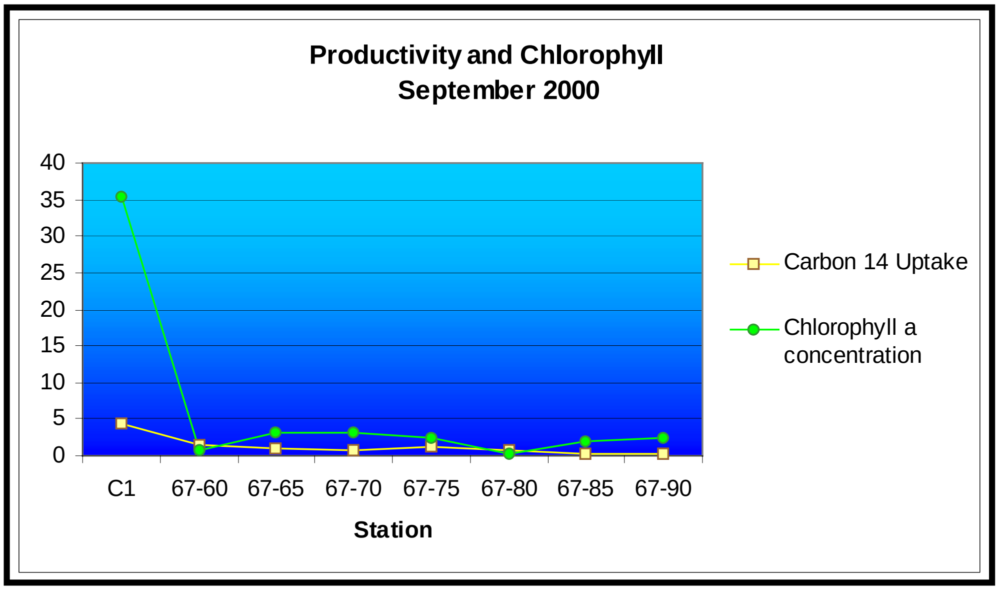

FIG. 5. Comparison between *in situ* chlorophyll concentration *a* (mg/m^3) and productivity (dg C/m^3/day) for CalCOFI line 67during September 2000.

6. Conclusions

In light of the fact that measured chlorophyll concentrations and CTD cast fluorometer readings bode poorly in the face of SeaWiFS derived data that correlate well with measured productivity, the satellite sensor appears to be invaluable. Furthermore, SeaWiFS data give the best approximation of actual productivity occurring at all stations including station C1 which is within 100 km of the coast. This is in contrast to the findings of MacFadyen (1998).

In situ data were spatially consistent with satellite-derived data. However, temporally these data were collected in a matter of days where SeaWiFS data were averaged over a month. Given the high variability of productivity, the close correlation to SeaWiFS data may simply be fortuitous. In addition, the close correlation of SeaWiFS data to productivity within each cruise compared to the poor correlation overall, suggests possibly a different algorithm was being employed for each period. Although April was characterized as an upwelling period, productivity values were comparable to September for all stations. High chlorophyll concentrations at C1 in September would imply productivity levels higher than observed. However, other factors that influence productivity such as nutrient levels and water temperature were not examined in this work. Photosynthesis is enzymatically controlled and cold sea surface temperature could be one possible explanation for observed productivity levels in April. In contrast, September was not characterized as an upwelling period. Thus, a lack of nutrients may address these observed values.

The data examined in this case are very localized spatially and temporally. The SeaWiFS sensor has been recording data for less than four years. Although the findings are encouraging, data spanning greater time series and regions would be necessary to validate these conclusions.

REFERENCES

Cotton, Leslie 1998: *Phytoplankton photosynthesis: can we measure it using fluorescence?* Monterey Bay Aquarium Research Institute. 7 pp.

MacFadyen, Amy 1998: *Modeling primary productivity from satellite-derived chlorophyll in the Monterey Bay region.* Monterey Bay Aquarium Research Institute. 19 pp.

NASA, cited 2001: SeaWiFS Project. [Available on-line from http://seawifs.gsfc.nasa.gov/SEAWIFS.html.]

Pennington, J. Timothy, Francisco P. Chavez, 1999: Seasonal fluctuations of temperature, salinity, nitrate, chlorophyll and primary production at station H3/M1 over 1989-1996 in Monterey Bay, California. *Deep-Sea Research II*, **47**, 947-973.

Ruddick, Kevin George, Fabrice Ovidio, and Machteld Rijkeboer, 2000: Atmospheric correction of SeaWiFS imagery for turbid coastal and inland waters. *Applied Optics*, **39**, 897-912.

APPENDIX A

DATA